

COLD GAS AT HIGH REDSHIFT

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Abstract.

We discuss the current observational and theoretical issues concerning cold gas at high redshift and present simulations showing how a number of observational issues can be resolved with planned future instrumentation.

1. Introduction

The observable history of the universe is dominated by a long phase from the epoch of recombination (at redshift 1500) to the reheating and reionization phase (perhaps near redshift 7) when the entire intergalactic medium is cold neutral gas. Current limits from QSO absorption line studies place this epoch above redshift 5. The fluctuations in this gas are so small that it is difficult to see either in emission or absorption (Scott and Rees 1990). However, it is an interesting scientific goal to try to observe this cool component of the intergalactic medium at high redshift. The only objects we know something about at the highest redshifts are the quasars. The space density of high redshift quasars clearly exhibit a steep rise and fall about a redshift of 2-3 (Shaver 1995) and the rise may be associated with the onset of galaxy formation.

In adiabatic models, where massive pancake structures formed and subsequently lumps of order the size of galaxies fragmented out of their collapse, the atomic masses of the cool gaseous pancake structures were estimated to be up to $\sim 10^{14} - 10^{15} M_{\odot}$. If such masses of diffuse atomic gas existed at $z \sim 3.5$, they would already have been detected by current

searches (Wieringa, De Bruyn and Katgert 1992 and references therein). Their non-detection can now be understood in light of the constraints set by microwave background studies and related research on the fluctuation spectrum (c.f. Scott, Silk and White 1995). The relative smoothness of the density fluctuations and the essentially mandated bottom-up nature of the galaxy formation process greatly limits the possibilities for directly observing proto-cluster size fluctuations in the cool gas phase. More ingenious methods, which probe both smaller and larger angular scales and in particular smaller masses, are likely to be required as discussed later.

Great hopes for this meeting lay in a number of reported observations of molecules observed at high redshift. However, while there are still very interesting as yet unconfirmed claims of large molecular masses of CO at high redshift the only well confirmed CO observations seen in emission are due to the two well known gravitational lensed objects the Cloverleaf and FSC 10214+4724 (Barvainis 1995, Scoville et al 1995, and Frayer 1995). There have also been several detections of CO in absorption against background radio sources in the mm band but also associated with lensing (Combes and Wiklind, these proceedings).

With combined Keck and HST data, remarkable progress has been made in the study of the absorption lines of QSOs and the objects that are associated with the absorbing material. The population of Lyman Alpha clouds can have a number of progenitors as we shall discuss. Both the Damped Lyman Alpha (DLA) systems and the Lyman Alpha forest lines may account for a significant fraction of the currently observed baryonic content of galaxies (c.f. Storrie-Lombardi et al 1995).

In this review of a very large subject we focus on a brief observational and theoretical overview of the subject of cool gas in the universe. In particular we present 9 figures that show how current and planned future instrumentation can detect and image cool gas at high redshift and indicate how such observations may help resolve some of the key issues.

2. Neutral Gas

There are now several new aspects to the study of Lyman Alpha absorption systems (c.f. Meylan 1995). From the point of view of this workshop it seems most interesting to emphasize that recently there has been a significant change in ideas about the origin of the Lyman Alpha systems. In particular they seem to have correlation scales of order ~ 1 Mpc and cannot be associated directly with individual galaxies. Structure formation can produce sheetlike debris of low column density that can account for many of the properties of the absorption lines. More generally, remarkable simulations presented at this meeting indicate that the distribution of the

absorbers can be obtained in N-body/SPH simulations.

Figure 1. We show the limiting column densities that we can expect to detect with current and planned instrumentation in the red-shifted 21 cm line. A background flux of 100 mJy is assumed, as well as a hydrogen spin temperature of 1000 K and a linewidth of 10 km s⁻¹. We compare these limits with the known distribution (from Petitjean *et al.* 1993) of the column density of absorbers derived from QSO absorption line studies.

At low red-shifts, it is clear that HI emission maps going to ever fainter column densities such as the map of M81 by Yun *et al.* (1994) are a most interesting compliment to the rapidly advancing knowledge we are obtaining from Keck and HST on the low column density environments of galaxies. There is no substitute for an unbiased spatial tracer of column density like that of an optically thin emission line. Unfortunately, the column density sensitivity in HI emission at a fixed physical resolution diminishes at least as rapidly as D_{Ang}^2 , so that only the highest column density disks will remain accessible out to large distances, and then only with the largest possible collecting areas, as we will see below.

However, lower column densities of HI can still be probed out to large distances using the HI 21 cm line in absorption. In Figure 1 we show the 5 σ limiting column densities in the 21 cm line that we can expect to detect with the up-graded, frequency-agile WSRT (Westerbork Synthesis Radio Telescope) and the proposed SKAI (Square Kilometer Array Interferometer, described by Braun in these proceedings) in a 24 hour integration. These limits were calculated with the conservative assumptions that only a relatively faint background source of 100 mJy flux be available and that the mean spin temperature of the gas be 1000 K. A brighter background source or cooler spin temperature result in a linear improvement of the column density limit. These detection limits are superposed on the observed number distribution of Lyman Alpha absorbers as function of column density (from Petitjean *et al.* 1993).

It is clear from the figure that the WSRT will allow access to the entire distribution of Damped Lyman Alpha systems ($N_{HI} > 10^{20.2}$ cm⁻²), while the SKAI will also permit study of much of the column density range of the Lyman limit systems ($10^{20.2} > N_{HI} > 10^{17}$ cm⁻²). The 21 cm data provide additional insight into the physical properties of the absorbing gas via an estimate of the effective spin temperature, as well as providing an opportunity to image absorber structure at milli-arcsec resolution utilizing VLBI (Very Long Baseline Interferometry). The equation relating the HI column density and the 21 cm line opacity is:

$$N_{HI} = \frac{32\pi k \nu_{21}^2}{3hc^3 A_{21}} T_S \int \tau dV \quad (1)$$

$$= 1.83 \times 10^{18} T_S \int \tau dV \quad \text{cm}^{-2} \quad (2)$$

independent of redshift, for V in units of km s^{-1} .

Direct imaging in HI 21 cm emission is the only reliable method for determining atomic gas masses. Current efforts have been limited both by instrumental sensitivity and by accessible frequency coverage to redshifts less than about 0.1. The situation is summarized in Figure 2, where “Detection” and “Imaging” atomic masses are shown as a function of redshift for the WSRT and the SKAI for an integration time of 100 hours. “Detection” has been defined as requiring a 5σ signal in a single 50 km s^{-1} velocity channel, while “Imaging” has been defined as requiring a 5σ signal in each of 6 independent 50 km s^{-1} velocity channels. The dotted line between redshifts of 0.2 and 2.5 for the WSRT indicates the frequency range where receiver systems, while available, are not yet optimized and are about a factor of 2–3 worse than shown. The atomic gas masses of the well-known nearby systems M33 and M101 have been included for reference in the figure, as well as the atomic gas mass of the ultra-luminous FIR galaxy, III Zw 35.

As can be seen in the figure, gas-rich systems will soon be detectable out to redshifts of a few tenths with the WSRT. The SKAI, on the other hand, will allow detection of even low mass spirals like M33 to $z > 1$ and gas-rich systems to $z = 3$ or more.

Since every narrow velocity interval is so sparsely populated with condensed atomic gas (at least since the epoch of re-ionization) observations of this type will not be source confusion limited, even with only a modest angular resolution of several arcmin. (This same comment applies to all emission line tracers of high redshift gas, except perhaps where the redshift has placed the line frequency near another emission line of Galactic or terrestrial origin.)

Figure 2. We show the detection (5σ in 50 km s^{-1}) and imaging (5σ in six channels of 50 km s^{-1}) limits of atomic gas mass as a function of redshift with current and planned instrumentation.

An important point to note is that the explicit redshift dependence of the equation for the atomic gas mass in terms of the observed 21 cm line integral is not often stated. For clarity, we give the equation below for an optically thin distribution of neutral hydrogen:

$$M_{HI} = \frac{16\pi m_H D_L^2}{3hcA_{21}(1+z)} \int S_\nu dV \quad (3)$$

$$= 2.35 \times 10^5 \frac{D_L^2}{(1+z)} \int S_\nu dV \quad M_\odot \quad (4)$$

for the luminosity distance D_L in Mpc, and the line integral in Jy km s⁻¹.

3. Molecular Gas

Molecular hydrogen gas is seen directly in the optical band in only one high redshift QSO absorption-line system 0528-25 at redshift 2.8. In the millimeter band, four objects have now been observed which show high redshift absorption in various molecules (CO, HCO+, HCN, O₂) generally associated with absorbers in gravitationally lensed systems (c.f. Combes and Wiklind, these proceedings). Actual conditions in proto-galaxies, etc. are not yet clear enough to make solid predictions, but it is obvious that molecular studies at high redshift have much to tell us in the near future. With conditions similar to, say, our Galaxy, gas phase and surface reactions produce molecular species readily on short time scales $\sim 10^6 - 10^7$ yr. Molecular hydrogen will form rapidly once the density and column density are high enough. A thorough discussion of the physical conditions and the constraints imposed on the H₂ species are given in Black et al (1987). Shielding by dust may be a crucial ingredient but probably the most important parameter is the strongly evolving background radiation field.

The beautiful data on the two lensed objects that show CO emission at high redshift are well described at this meeting by Barvainis and Scoville for the Cloverleaf and F10214+4724 respectively.

Frazer (1995) reviews the current evidence for detection of CO emission at high redshift. Only very tentative detections have yet been made in non-lensed systems. When detected at modest redshift ($z \sim 0.1$), the empirical Galactic conversion factor suggests molecular gas masses of a few times $10^{10} M_\odot$ concentrated within regions of a few kpc in diameter (Scoville et al. 1991). However, it has not yet been demonstrated that a similar conversion factor of CO luminosity to molecular hydrogen mass need apply under the extreme physical circumstances of circumnuclear starbursts. Even when multiple CO line transitions are observed, it is worrisome that they need not necessarily arise from regions sharing the same physical conditions, so that the line ratios may remain difficult to interpret.

An impression of the current and future capabilities for imaging molecular mass at high redshift via associated CO emission is given for an 8 hour integration in Figure 3. The empirical Galactic conversion factor (eg. Scoville et al. 1991) gives:

$$M_{H_2} = 1.2 \times 10^4 \frac{D_L^2}{(1+z)} \int S_{CO1 \rightarrow 0} dV \quad M_\odot \quad (5)$$

for the luminosity distance D_L in Mpc, and the CO 1→0 line integral in Jy km s⁻¹. If another CO line transition is used then the constant in eqn. 5 should be scaled in accordance with the ratio of line luminosities (in erg s⁻¹). We have defined “detection” and “imaging” as before for the atomic gas mass above and assumed that the CO 2→1 transition would be observed with a 3 times higher line luminosity than that of CO 1→0. Nearby normal spirals and two ultra-luminous FIR systems are included for reference in the figure. The question marks are used to indicate the uncertainty in assigning a molecular mass to the observed emission line luminosity in the case of the extreme starburst systems.

From Figure 3 it is clear that the MMA (the proposed NRAO Millimeter Array) should allow study of unlensed ultra-luminous systems out to redshifts greater than 1, although normal spirals will only be accessible out to about a tenth.

Figure 3. We show the detection (5σ in 50 km s⁻¹) and imaging (5σ in six channels of 50 km s⁻¹) limits of molecular gas mass utilizing the CO 2→1 transition as a function of redshift with current and planned instrumentation.

Megamasers are frequently seen in association with relatively edge-on starburst galaxies and it may well be worth searching systematically for megamasers at high redshift since their luminosities are so large. Megamaser emission in the OH, H₂CO and H₂O lines is a valuable probe of circumnuclear kinematics with ultra-high angular resolution and once the theory adequately catches up with the observations it may also be of help in understanding the physical conditions in extreme star-bursting systems.

In Figure 4 we show the detection and imaging limits of OH megamaser emission in a 24 hour integration. Reference luminosities of the sources in III Zw 35 and IR20100-4156 are indicated as well as the kilomaser emission seen in NGC 253. Comparable luminosities to those of OH in III Zw 35 are also seen in the H₂CO and H₂O megamaser sources (Henkel and Wilson 1990, Baan et al. 1993, Henkel et al. 1984). With the added frequency coverage of the upgraded WSRT, megamaser emission should already be detectable to red-shifts greater than about 1, while the added sensitivity of the SKAI should allow such sources to be studied in detail at any redshift.

Figure 4. We show the detection (5σ in 50 km s⁻¹) and imaging (5σ in six channels of 50 km s⁻¹) limits for OH mega-maser emission as a function of redshift with current and planned instrumentation.

There have been reports of ultra cold gas that could constitute a significant fraction of the dark matter in the Universe (Lequeux, Allen and

Guilloteau 1993, Pfenninger and Combes 1994, Gerhard and Silk 1995). The absence of such gas in the absorption line spectra of QSOs indicates that the covering factor of this gas in a sight-line to a distant QSO is less than $\leq 1\%$. This limit may be a severe constraint on the proposal that such cold gas is a major constituent of the Universe.

4. Dust

Some time ago, Ostriker and Heisler (1984) proposed that the observed fall off in QSO number density might be due to obscuration by dust. The excellent study of Shaver (1995) shows that this is not the case. More moderate obscuration is probably present giving variations in the inferred number counts as a function of redshift for QSOs of less than order unity. This is consistent with calculations done by Fall and Pei (1994).

The importance of radio surveys cannot be underestimated here since a complete radio survey can be used independent of the dust obscuration and as noted by Shaver (1995) quasars at redshift $z = 6$ can be easily seen once the target radio source is known.

Submillimetre observations at high redshift (Isaak et al 1994, McMahon et al 1994) show that dust masses at redshifts $z = 4 - 5$ of order $10^8 M_\odot$ and temperatures of say 60 K can already be detected. Protogalaxies may have such dust masses after an initial burst of star formation and a more or less immediate ($10^6 - 10^7 yr$) giant and supergiant dust producing phase. Conversion of observed continuum luminosities to actual dust masses remains very tricky while the emission spectrum is only poorly sampled and there may well be multiple temperature components present.

In Figure 5 we illustrate the possibility for detecting dust continuum emission via an 8 hour observation at 230 GHz with the heterodyne receiver system of the JCMT and the proposed MMA. Dust emission spectra were calculated with a modified black body ($\nu^{1.5} B(T, \nu)$) using dust temperatures of 60 K (solid curves) and 30 K (dashed curves). The ratio of rest-frame 100 μm to 230 GHz flux density in these cases is 1800 and 360 respectively. “Detection” is defined as requiring a 5σ signal and “Imaging” a 30σ signal. Reference luminosities of normal spirals and the ultra-luminous systems III Zw 35 and B1202-0725 are indicated. Single (sub-)millimeter dishes will be able to do better than the indicated heterodyne JCMT performance through the use of high bandwidth bolometric detectors (such as SCUBA). This detection method is not yet applicable to coherent, high resolution imaging with an interferometric array, although the development of “hot electron bolometers” may make this a possibility in the future.

From the figure it is clear that the dust continuum becomes more accessible to a 230 GHz observation beyond $z = 1$ for dust temperatures greater

Figure 5. We show the limiting luminosity for a continuum observation at 230 GHz for detection (5σ) and imaging (30σ) of the dust continuum as a function of redshift for current and planned instrumentation. The solid curves are for a modified black body ($\nu^{1.5}B(T, \nu)$) using a dust temperature of 60 K, while the dashed curves are for a dust temperature of 30 K.

than about 30 K. However, current sensitivities will limit detection to extreme systems, like B1202-0725, and even then these will be preferentially found at $z < 0.3$ and perhaps at $z > 3$. The MMA will allow comparable detections on less extreme systems (with L_{FIR} “only” $\sim 10^{12} L_{\odot}$). Dust continuum from normal spirals like M33 and M101 will still only be accessible in the local universe.

Many authors have pointed out the excellent correlation of dust continuum emission and non-thermal radio continuum emission based on the many thousands of nearby galaxies detected with IRAS. Although still not understood in detail, there appears to be a strong coupling of both emission tracers to the massive star formation rate. With this in mind, we have illustrated in Figure 6 the limiting 1.4 GHz luminosities of current and planned instrumentation as a function of redshift. A power law emission spectrum of the form $S \propto \nu^{-0.7}$ has been assumed. Detection and imaging of luminous star-bursting systems should already be possible with the VLA out to $z > 1$. The greater sensitivity of the SKAI will allow even normal spiral galaxies to be visible out to cosmological distances.

In this case, of observing the faint continuum emission from distant sources, it is critical that enough angular resolution be employed so that source confusion does not limit the sensitivity of an observation. The deepest existing radio continuum observations, as well as experience with the HST, suggest that angular resolutions of 0.1–1 arcsec are sufficient to completely circumvent the problem of source confusion. It is for this reason that the curves in Figure 6 have been drawn for the VLA (the NRAO Very Large Array) and SKAI, where such angular resolutions will be achievable, rather than for the WSRT, for which continuum source confusion at faint flux levels will be a limitation.

Figure 6. We show the limiting luminosity for a continuum observation at 1.4 GHz for detection (5σ) and imaging (30σ) of the non-thermal continuum associated with massive star formation as a function of redshift for current and planned instrumentation. The curves assume a power law spectrum of the form $S \propto \nu^{-0.7}$.

5. Cosmology: The Cool Gas History of the Universe

Observational tests for the detection of the cool pre-ionization ($z \geq 5$) IGM have been considered by Scott and Rees (1990, also see Kumar et al. 1995). If the hydrogen spin temperature is greater than the CMB temperature (T_R) at these epochs an emission signature from neutral hydrogen would be expected. Proto-cluster mass enhancements are likely to have total masses of $10^{15} M_\odot$ on proper scales of less than about 3 Mpc, corresponding to less than about 15 arcmin at $z = 6$. The instrument best-matched to this problem would have a comparable beam size of some 15 arcmin at an observing frequency of 200 MHz. The necessary telescope diameter of some 350 m corresponds roughly to that of the individual elements of the SKAI.

An observing mode that is being envisioned for SKAI is one whereby the auto-correlations of the individual elements are incoherently summed to give a \sqrt{N} increased sensitivity over an individual element, which still falls short by \sqrt{N} from the sensitivity of the coherently combined data, but has a factor of about 10^4 greater brightness sensitivity. In this mode atomic gas masses of $6 \times 10^{11} M_\odot$ could still be detected at $z = 6$. As long as the mass fraction of neutral atomic hydrogen is greater than about 6×10^{-4} then proto-cluster enhancements should be seen. In the case of the GMRT (the Giant Meterwave Radio Telescope), the limiting neutral atomic fraction for proto-cluster detection is about 0.025 (Kumar et al. 1995).

An interesting alternate possibility is that the HI may be observable in absorption, particularly for high baryon density Universes where the effect of collisions can drive down the spin temperature, T_S , below the cosmic background radiation temperature, T_R . For a clumpy gas distribution at high redshift the resulting spin temperature and column density variation can produce a patchy structure across the sky. Since the HI brightness temperature is given by:

$$T_B = T_S(1 - e^{-\tau}) - T_R(1 - e^{-\tau}) \quad (6)$$

the absorption detection signature will be a factor of T_R/T_S stronger than that in emission. In the most extreme scenarios, Scott and Rees predict $T_R/T_S = 10$, resulting in an easily detectable signal for instruments like SKAI and possibly the GMRT operating near 200 MHz.

Generally, massive structures are needed to produce a currently observable effect. However from the work of Steinmetz (1995) and Kauffman (these proceedings) it is clear that in the standard bottom up scenarios there are not many really big lumps of neutral gas at high redshift but there are many small lumps clustering up to large scales but only at the present epoch. A particularly interesting way to view this is with the tree

diagrams in Lacey and Cole (1994) that indicate how the dark matter halos put themselves together hierarchically to form larger galaxies.

6. Active Galaxies, Radio Galaxies and Quasars

Although it has proved exceedingly difficult to detect the extended gaseous halo structure around protogalaxies (Djorgovskii et al 1995) it has been far more productive to look around active galaxies. Large masses of ionized and cool gas have been found around high redshift galaxies (c.f. McCarthy 1989). Similarly interesting results can be found in Röttgering et al (1995) and Van Ojik (1995).

Very recently, however, detections of luminous Lyman Alpha emission from protogalaxies at high redshift are emerging from detailed studies using HST and Keck (Giavalisco et al 1995, Moller et al 1995). Typically, we might expect the masses of HI associated with the Lyman Alpha emitter to be of order $10^{10} M_{\odot}$ although this depends on a number of uncertain parameters such as the ionization balance, etc. Figure 2 suggests that such atomic gas masses should be detectable with SKAI out to $z \sim 3$.

7. Galaxy Formation: Can it be Observed as Cool Gas?

Interestingly, there now seems to be a consensus building about the pattern of galaxy evolution from combined HST and ground based (CFHT, Keck) data (Lilly et al. 1995, Driver et al 1995, Griffiths et al 1995). Massive galaxies do not seem to be evolving whereas smaller dwarf irregulars seem to burst into life between a redshift of $z = 0.5 - 1$ and then fade away by the current epoch. This pushes back the epoch of massive galaxy formation to redshifts of order $z \geq 3$.

Figure 7. Simulated spectra of the low mass spiral galaxy M33 are shown for frequencies between about 10^8 and 10^{14} Hz after being red-shifted to $z = 0.25, 1$ and 4 , under the assumption of no spectral evolution. Instrumental sensitivities (1σ) of existing and planned instruments are overlaid for both spectral line observations (top panel) and continuum observations (bottom panel). Spectral line IDs for some of the major emission lines are indicated at $z = 0$.

We note in passing that, apart from the standard collapse and infall of HI, there are large masses of hot gas such as those associated with cooling flows in clusters that have cooler denser material at their centers. In fact large HI masses are inferred from shadowing effects (Allen and Fabian 1994). What this might be like at higher redshift has been discussed recently by Nulsen and Fabian (1995). Interesting limits on the cold gas content of the intracluster medium for nearby clusters of galaxies indicate

that the total cold neutral gas content in the central regions of such clusters is $\leq 10^9 M_\odot$ (O’Dea et al 1995).

Current theories of galaxy formation (c.f. Navarro, Frenk and White 1995) indicate that typical galaxy masses increase as a function of redshift from dwarf galaxy sized objects at redshifts of order a few to more massive galaxies at redshift of order unity to cluster sized objects at the current epoch. We next illustrate how our observational capabilities overlay the redshifted spectral energy distributions of several galaxy types and masses.

Figure 8. Simulated spectra of the massive spiral galaxy M101 are shown for frequencies between about 10^8 and 10^{14} Hz after being red-shifted to $z = 0.25, 1$ and 4 , under the assumption of no spectral evolution. Instrumental sensitivities (1σ) of existing and planned instruments are overlaid for both spectral line observations (top panel) and continuum observations (bottom panel). Spectral line IDs for some of the major emission lines are indicated at $z = 0$.

In Figure 7 we show a simulated spectral energy distribution of the low mass spiral galaxy M33 redshifted to $z = 0.25, 1$ and 4 assuming no spectral evolution. In the top panel we have overlaid the 1σ sensitivity at a spectral resolution of 10^4 of a variety of existing and planned instruments on these spectra. Comparison of the instrument sensitivities with emission line intensities in the spectra illustrates out to what redshift such an object might be studied. In the lower panel the same spectra are overlaid with 1σ continuum sensitivities of the same instruments. In this case the sensitivities should be compared with the flux densities of the continua to assess out to what redshift the object might be studied. Integration times of “one transit” were assumed which were typically 8 hours for ground-based telescopes and 10^4 seconds for satellite observatories. The various line and continuum emission components in the model spectra are described in detail in Braun (1992). A similar set of redshifted spectra and overlaid instrumental capabilities are shown for the luminous spiral galaxy M101 in Figure 8. In Figure 9 we show the same plots for the ultraluminous FIR starburst galaxy III Zw 35 including its observed megamaser emission in OH and H_2CO .

Figure 9. Simulated spectra of the luminous starburst galaxy III Zw 35 are shown for frequencies between about 10^8 and 10^{14} Hz after being red-shifted to $z = 0.25, 1$ and 4 , under the assumption of no spectral evolution. Instrumental sensitivities (1σ) of existing and planned instruments are overlaid for both spectral line observations (top panel) and continuum observations (bottom panel). Spectral line IDs for some of the major emission lines are indicated at $z = 0$.

Comparison of the redshifted model spectra with our current and projected observational capabilities (in Figs. 7–9) gives us grounds for guarded optimism about our prospects for studying the galaxy formation process.

Near $z = 1$ we should be able to give a very good characterization of the types of objects which have formed via their atomic masses and the luminosities of the molecular, dust and stellar components. The more massive and luminous end of the distribution can be tracked all the way out to $z > 4$, while even the low mass end of the distribution should yield its secrets out to $z \sim 0.5$. New instrumentation will be critical to realizing this goal. The unprecedented sensitivity of the VLT and Keck will be necessary to permit optical and near-IR spectroscopy to identify these distant systems. Similarly, the next generation of cm/dm and mm/sub-mm arrays (SKAI and the MMA) will be needed to ascertain the associated cool gaseous masses and its kinematics. And although ISO makes an important contribution to the intervening frequency interval, it is clear that a new mission with SIRTIF (or better) sensitivity will be needed to effectively fill in the mid-IR to FIR gap.

Great progress is being made in studying the Universe at high redshift at present by work done with Keck and HST. After completing this paper and contemplating the results of the simulations it is clear that extraordinary progress can be made with the planned instrumentation. It is obvious how the proposed studies at longer wavelengths from low frequency radio to sub-millimeter can give vital information in our quest to understand the physics of the Universe at high redshift when it was a fraction of its current age.

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